Chapter 5: Vacuum

A particle accelerator abhors a vacuum.
- Aristotle

The beam tube in the Main Injector, as with any accelerator, must be kept under vacuum. Whatever air molecules may be in the pipe, act as obstacles to the circulating protons and antiprotons. Sometimes the particles are disturbed to the point where the beam quality is degraded, and sometimes they are scattered out of the beam pipe altogether.

Unlike the Antiproton Source and the Tevatron, in which the particles must circulate for hours, days, or weeks, beam in Main Injector is never in the machine for more than a few seconds. Although a “few seconds” may mean hundreds of thousands of revolutions, the vacuum requirements are not quite as stringent as with accelerators in which beam is stored.

The quality of vacuum is frequently measured in units called torr. Atmospheric pressure is traditionally measured in inches or millimeters of mercury as measured by a barometer. One torr represents one millimeter of atmospheric pressure. For comparison, pressure at sea level is 760 torr (except during hurricane season). Vacuum in the Main Injector is in the neighborhood of 2 X 10^{-8} torr. Another unit of pressure is the micron. One torr is equivalent to 1,000 microns.

Vacuum Pumps

Different types of vacuum pumps are effective at different pressures. The beam pipe in the Main Injector, if starting from atmospheric pressure, is pumped down in three stages, using roughing pumps, turbo molecular pumps, and ion pumps, in that order. Of these, only the ion pumps are permanently affixed to the ring, and are responsible for maintaining the high vacuum in the pipe. The roughing pumps and turbo pumps, combined as a unit, are on portable carts. They are moved to locations where the vacuum is especially poor, as during initial pump down.

Roughing Pumps and Turbo Pumps

A roughing pump uses a mechanical piston to remove air from the beam tube. It is the only type of pump effective at atmospheric pressure. It is capable of pumping down to about 10 torr.

The turbo pumps are multi-tiered “fans” which drive the air molecules out of the pipe. They are turned on when the roughing pump has removed what it can. The blades spin at a rate of several tens of thousands of RPM; the ends of the blades are actually moving faster than the molecules they are trying to hit. The turbo will pump the beam pipe down to approximately 10^{-5} torr.

There are about ten carts with the roughing/turbo combination available for responding to vacuum problems in the Main Injector. If everything is running well, none of the carts are needed. The units are connected as needed at the pump out ports at the downstream side of some of the main quadrupoles.

Pumping Ions

Any pumping scheme that expels air outside the system, such as the roughing and turbo pumps, will have some problems with “back-streaming,” or the tendency for air to slip in from the outside. Ion pumps avoid this problem because, as they take over from the turbo pumps at about 10^{-6} torr, there are so few molecules left that they can just be swept under the rug. They are literally buried in the pump itself.

Inside an ion pump, 5200V is placed across a stainless steel anode and a titanium cathode. Free electrons in the electric field will be accelerated and strike the air molecules, freeing even more electrons. The resulting positive ions will also pick up energy from the electric field and be pulled toward the cathode. The more chemically reactive molecules, such as oxygen (and to a lesser extent, nitrogen) will combine chemically with the titanium. Other molecules, such as the chemically inert argon, may still have enough energy to bury themselves in the metal of the cathode.

The high voltage for the ion pumps comes from individual power supplies in the service buildings. Red cables (a safety standard for high voltage) connect the power supplies to the pumps. It is important not to use wet dirty scissors when severing the cable.

The cathode and anode assemblage is encapsulated in permanent magnets, which bathe the components in a magnetic field of about one-kilogauss. The magnetic field causes all of the charged particles to spiral, increasing their path length and their chances for ionization.

The pumping capacity of an ion pump is measured in units of liters/second (L/S). It may be difficult to interpret that unit literally, but it is proportional to the number of ions removed from the beam pipe. The vast majority of ion pumps in the Main Injector ring are 30 L/S. There are a few locations that need powerful pumps, such as the regions connected to beam transfer lines and near the RF cavities. The ion pumps used in these critical regions have a capacity of either 300 L/S or 600 L/S.

The density of ion pumps in the tunnel is high, three per half-cell in the normal arcs, and two per half-cell in the dispersion-suppressor regions. They are named by adding a digit to the location number. For example, at 629, a location in a normal arc, IP6290 is the pump between the Q629 and the “A” dipole just downstream, IP6291 is between the “A” dipole and the “B” dipole, and IP6292 is downstream of the “B” dipole (IP6292 looks as if it belongs to the downstream location, but it doesn’t). Fig. 2-19 illustrates ion pump nomenclature used around a main quadrupole.

The dispersion-suppressor cells are shorter and only require two pumps. For example, at 639 there is no ion pump between the quad and the “C” dipole; IP6391 is between the “C” and “D” dipoles, and IP6392 is downstream of the “D” dipole.

In the straight sections, the ion pumps are given letter designations. For example, at Q100, where the MI-8 line meets the Main Injector ring, the ion pumps are designated IP100A through IP100G.

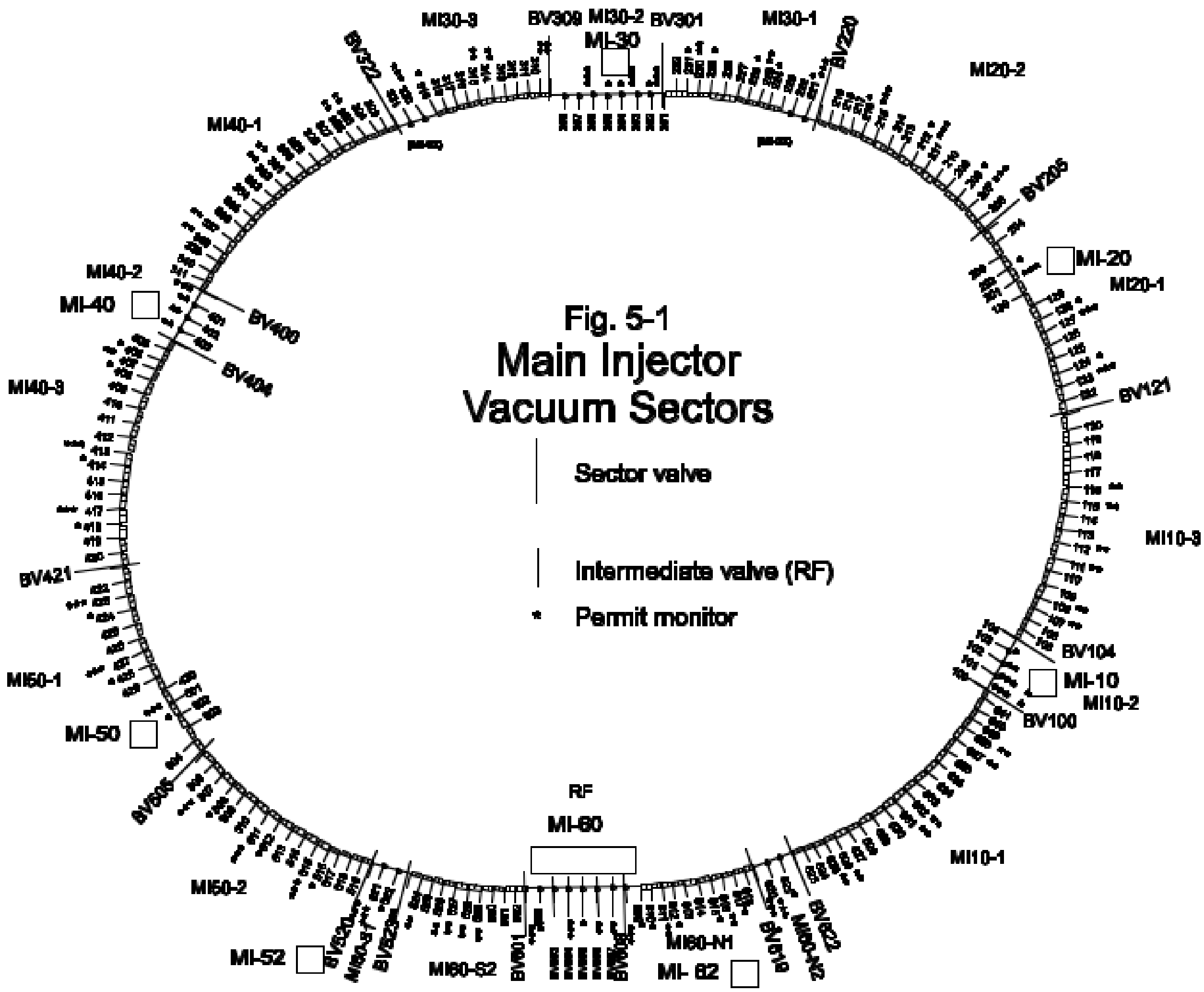
More details on the various beam line vacuum systems will be included in the chapter on Beam Transfer Lines.

Under normal circumstances, the ion pumps are sufficient to maintain vacuum in the Main Injector ring. If, however, there is an air leak, the pump will respond by drawing more current as it impounds the air molecules. If vacuum becomes worse than, say, 10^{-5} torr, or if the pump is shorted, the titanium cathode will overheat and begin to outgas its store of trapped molecules. At that point, using the ion pump to improve vacuum has become a losing proposition, and it trips off. If the leak is bad enough, what will often happen is that several pumps will trip off sequentially as they try to take over the work of those who have fallen before them. Sometimes it is possible to turn the pumps back on after they have had a few minutes to cool, but if not, an access has to be made to fix the leak, and the turbo pumps brought in to recover the vacuum.

Sector Valves

[Author's note: This section describes, among other things, how the sector valves are interlocked to the ion pumps. That is the Once and Future Plan. However, during the commissioning phase, when the new pipe was laden with trapped gases and the beam was not yet properly tuned, the valves would close so frequently that commissioning became impractical. Since that time, the valves have been interlocked only to the Pirani, which are less sensitive. At some point in the future the ion pumps will be used again for interlocking.]

The beam pipe in the Main Injector ring is divided into 18 vacuum sectors (see Fig. 5-1 on the next page). Sector valves can close to create a barrier to bad vacuum, thereby isolating vacuum problems to relatively short sections of the ring.



(Unfortunately, the valves are also effective barriers to the beam; they are often referred to as beam valves.) The status of the valves can be read through the controls system. The beam valves are designated "BV" followed by the location number.

The length of the sectors varies. The beam valves are close together where vacuum activity is particularly intense, or where there are connections to external beamlines. Sector valves bound most of the straight sections. The RF Sector has several beam valves internal to the sector, called intermediate valves, for isolating short groups of RF cavities.

On the vacuum applications page, the sectors are usually named for the service building where its equipment resides, and numbered consecutively if there is more than one sector associated with a service building, e.g. MI10-1, MI10-2, and MI10-3. Locally, however, inside the service building, the sectors are labeled for the first location (proton direction) in the sector; the same three sectors at MI-10 are labeled #622, #100, and #104.

The sector valves can be closed manually, but they are also interlocked to selected readbacks from the ion pumps. Except for MI-60 and some of the very short sectors, each sector has three sets of ion pumps that can be used to interlock the valves. Each set includes four pumps; at least two of them need to be on in order to grant a permit (see Fig. 5-2).

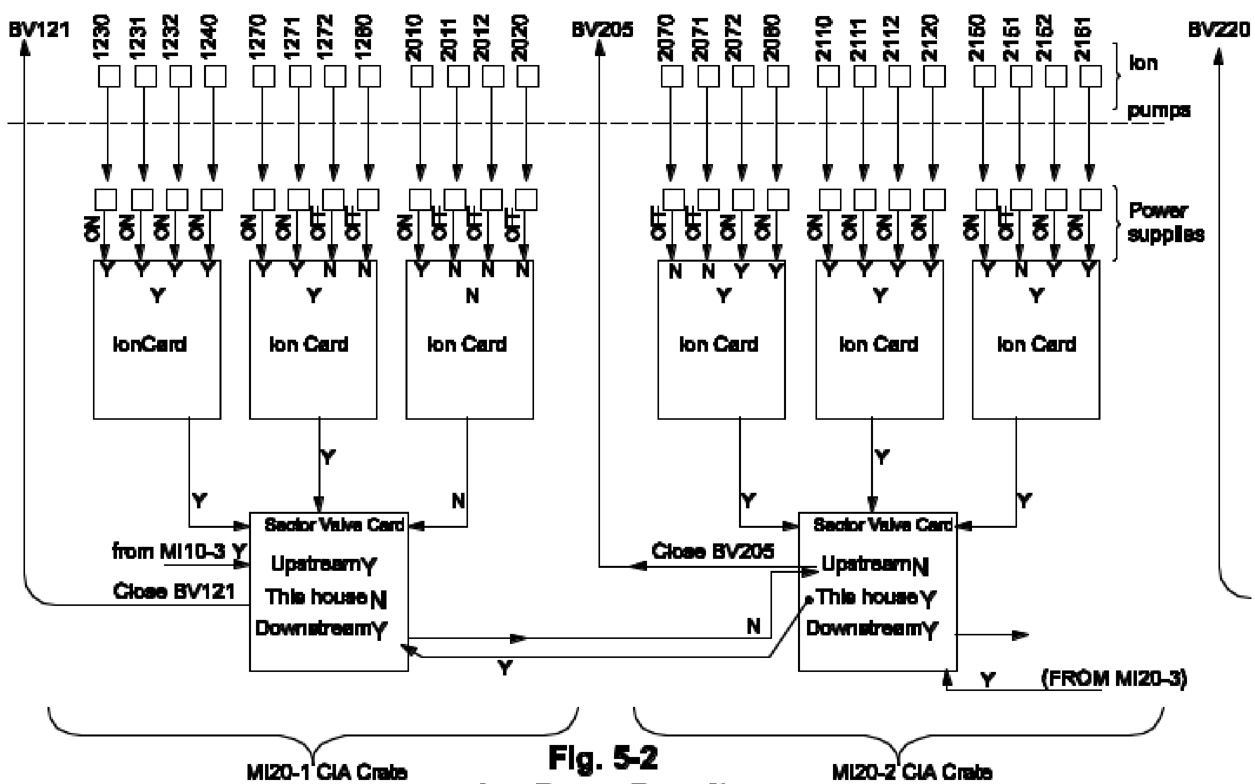


Fig. 5-2
Ion Pump Permits

In this diagram, a vacuum problem has begun to develop near BV205; a majority of the pumps in the downstream block have tripped off. The block has sent a "NO" vote to the permit and for M220-1, so BV121 and BV205 are ordered to close. Compare to Fig. 5-1.

Readers should ask themselves, if either 2072 or 2080 trip off, will BV220 also close?

If a beam valve between two sectors is to be opened, a permit must be obtained from both the upstream and downstream sectors. For example, in order to open BV205, permits must be granted from both MI20-1 and MI20-2.

Two beam valves, BV301 and BV309, are used by the safety system to control circulating beam in the Main Injector ring. The valves will close if the electrical permit is present and the radiation permit is not. (If the electrical permit is not present, it is impossible to circulate beam, and there is no need to close the valves.)

The sector valves are held open by air pressure. Air compressors at MI-20, MI-40, and MI-60S maintain pressure of 80 to 100 psig in copper tubes. The tubes enter the tunnel penetrations and run parallel to the cable trays on the ceiling; the pressurized air can be tapped from the tubes at intervals, and, of course, where there are sector valves. A failure of the air compressor to maintain pressure will eventually close the valves, although each valve is provided with a ballast tank. The valve will also shut in the event of a power failure. Unlike the old Main Ring, the air compressor is dedicated to the vacuum system, and is not shared with the LCW equipment.

The pressurized air can be (and usually is) sent through a unit that cools and dehumidifies the air before it enters the tunnel. The unit can be manually valved out if necessary.

Vacuum Instrumentation

There are two methods for measuring vacuum in the Main Injector. One is with a Pirani (Pe-RAH-nee) gauge. A Pirani (which have occasionally been known to skeletonize a cow in less than three minutes) works by heating a wire with a constant current source and measuring its resistance. The resistance of the wire increases with temperature. Air molecules near the wire carry away the heat. The better the vacuum, the fewer the air molecules and the hotter the wire, so the applications software as can interpret the resistance of the wire pressure. Pirani gauges read back measurements from normal atmospheric pressure down to 10^{-3} torr; they are most accurate at the lower end of that range.

One alias for a Pirani gauge is “convection” gauge, because heat is carried away by the convection of the air. There are two Pirani gauges in every sector, including the “sub sectors” in the RF sector. They are found near the bottom of the pump out port and can be recognized by their blue caps.

The second method of measuring vacuum is through the ion pumps themselves. The arc of an ion pump creates a current that can be read by the power supply. Since the current is proportional to the number of molecules ionized, it can be interpreted by applications software as pressure; the vacuum readback on an ion pump is derived from the arc current. The readback is valid for the range in which the ion pumps are active, from about 10^{-4} torr down to at least 10^{-9} torr.

Vacuum Controls

The applications program that interfaces with the vacuum system is called, inexplicably, “MI VACUUM.” It is found on Page I55 (no relation to the Stevenson Expressway). The program also interfaces with the Tevatron, Switchyard, and Booster vacuum systems.

The individual sub pages on I55, 8GeV, MI10-1, MI-10-2, etc., select which of the 18 sectors will be viewed. You can find the Pirani gauges readbacks from the and ion pumps on the “Main Page”; the status of the beam valves and their permit status is also here.

Locally, at the service buildings, the CIA crate controls the vacuum (Controls Interface Adapter). There are several kinds of cards in the CIA crate. As a rule, there is one ion card for every 6 ion pumps. The ion card gathers the readbacks from its little domain of ion pumps; the first four channels on each card can be used to establish the beam valve permits. (There are usually two ion pumps monitored by each ion card that are not represented on the front panel.) In most sectors, three cards, that is, 12 ion pumps, are tied into the beam valve permit. The three groups of pumps are spaced apart to more accurately sample the length of the sector. If three pumps within one of the selected groups fail, the permit is withdrawn and the beam valve closes.

The sector valve card is what actually decides whether a beam valve should close or not. It directly controls only the upstream beam valve for the sector. For example, Sector MI20-1 is bounded by BV121 and BV205. The sector valve card for MI20-1 is responsible for BV121, but the sector card for MI20-2 is responsible for BV205. In the situation represented by Fig. 5-2, IP2011, IP2012, and IP2020 have all tripped off. With the majority of the pumps off, the ion card representing those pumps, interpret the information as a vacuum problem that could spread to other sectors. It sends a "NO" bit to the sector card for MI20-1, which orders BV121 closed. It also sends a status bit to the "Upstream Permit" bit of the sector valve card for MI20-2, which responds by closing BV205.

Locally, on the CIA crate, the sector valve card displays the permit status and the open/closed status of each of the two valves. There is also a "request" bit that indicates that a valve has been asked to open but has not yet complied. The same information is available on I55 under the "Sector Valve" sub page.

Alarms are generated when any three consecutive ion pumps are off, or if 20% of the total number of pumps in a sector trip. The alarms are independent of the valve permits, but provide a warning that vacuum problems are developing.

The CIA crate interfaces to the outside world using an Arcnet loop, not through CAMAC as with some of the other machines. There is a 186-bearing card in the rightmost slot that functions as the interface. All of the CIA crates in the Main Injector talk to a dedicated VME front end, called MIVAC; MIVAC is located at MI60 south, Rack 123. The Arcnet loop uses the CATV cables (the same system that carries TV images) to relay data back and forth from the CIA crates to MIVAC. The VME, in turn, is linked to the general controls system through Ethernet.

The VME uses a MOOC software platform, so many of the controls related error messages will read back as MOOC errors.